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Special Article

Analysis of Rainfall Features and Calculation of Rainfall Pattern of Short Duration Rainstorm in Wuhan, China

Análisis de las características de precipitación y cálculo del modelo de precipitación de tormenta de corta duración en Wuhan, China

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Abstract

Based on data of daily rainfall in the 66 years from 1951 to 2016 and precipitation minute data of the heavy rainfall event (daily rainfall > 50 mm) in Wuhan, China, several methods such as linear tendency, cumulative distance, and statistical analysis were used to analyze the rainfall features and to calculate the Rainfall Pattern of Short Duration Storm. It is found that: 1) The average rainfall precipitation in Wuhan was 1260.9 mm from 1951 to 2016, the change trend of annual precipitation in the past 66 years existed two rises and falls. The obvious change happened in 1979. The rainfall mainly concentrated in between April and August, accounting for about 65.8%. 2) In Wuhan city 309 rainstorm days and 65 heavy rainstorm days happened in the past 66 years, each year 4.69 rainstorm days and 0.98 heavy rainstorm days happened, and

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among average five rainstorm days 1 day was heavy rain. The most number of 12 rainstorm days happened in 1991. The trend of maximum daily rainfall firstly descended from 1951 to 1983, and then it increased up to 2016. 3) The daily rainstorm variation since 2000 shows that the average precipitation of 80 rainstorms was 83.28 mm, the max hour rainfall peak happened at 11:00 am BJT, the maximum average 3-hours rainfall occurred between 10:00 am and 12:00 pm BJT, and the max of average 6-hours rainfall occurred between 07:00 am and 12:00 pm BJT. 4) The coefficient of rainfall peaks for 1-hour rainfall, RP3-1, was about 0.439, and coefficient of rainfall peaks for 2-hour rainfall, RP3-2 was about 0.481.

Keywords: Wuhan City, Rainfall Features, Short Duration Storm, Rainfall Pattern, Coefficient of Rainfall Peaks.

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Introduction

According to the latest National Bureau of statistics data, the rate of urbanization of China has reached 52.6% with the rapid development of China's Urbanization. Most of the population, wealth and infrastructure concentrate in large cities, and therefore, flood disaster losses in cities, caused by torrential rains, increase. The observation data of city flood show that its peak flow is several times or even ten times higher than the natural river basin flood in the same area. Floods constitute a serious threat to cities with a dense population, developed industry and commerce, and many buildings. At the same time, the continuous development of underground space tremendously changes the city environment and brings huge risks to the safety of flood control. In recent years, Beijing, Shanghai, Wuhan and other big cities have hit by rainstorms, causing great losses of people's lives and property (Wang, 2014).

Wuhan city has a special geographical position and obvious rainfall features. Four extraordinary floods occurred in Wuhan in 1931, 1954, 1998, and 2016. In particular, during the week of June 30th to July 6th, 2016, a continuous rainfall level exceeded the city's highest value since meteorological records began (up to 560.5 mm). This flood disaster in Wuhan led to the 740,000 acres of crops being damaged, 9758 houses collapsed or being damaged, and significant damage to the road

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infrastructure. The direct economic cost of the flood was 4.8 billion RMB. In order to prevent the rainstorm, some researches on rainfall features and rule and rainfall pattern have made. Chen, Yang and Tu (1999) given the daily variation feature of the last 100 Rainstorm and large Rainstorm in Wuhan. Yang *et al.* (2001) analyzed the change trends of heavy rainfall events for last 40 years in the Chang Jiang valley. Liu, Chen, and Zhang (2007) analyzed the precipitation characteristics in Hubei Province and their influence on flood/drought. Zhang, Qin and Chen (2008) analyzed the change Characteristics of precipitation in the Latest 56 Years in Wuhan. Wang, Zhang and Wang (2010) analyzed characteristics of short-duration precipitation extremes of Badong and Yichang in the Yangtze Three Gorges Area. Fischer *et al.* (2012) give the probability distribution of precipitation extremes in the Zhujiang River Basin, South China. In order to update the knowledge on Wuhan city drainage system, this paper analyzed the in Wuhan and calculates the rainfall pattern of short-duration storms based on previous studies. It has important practical significance for city waterlogging prevention, rational use of rainwater resources and the construction of sponge city.

Materials and Methods

Rainfall Data

With the improvement of modern meteorological service system, 50 automatic rain-gauges there installed in Wuhan. According to the requirements of the study and the history of rainfall rain-gauge, we selected the rain-gauge located in the East and West Lake District of Wuhan for analysis. The data were collected from a total of 66 years in Wuhan during 1951-2016. The precipitation level is divided into 10.0 mm from now on referred to as light rain, 10.0-24.9 mm for moderate rain, 25.0-49.9 mm for heavy rain, greater than or equal to 50.0 mm is called a rainstorm, and greater than or equal to 100.0 mm heavy rainstorm. Based on the selected in 1980-1999 single day rainfall greater than 100 mm and the daily precipitation more than 50 mm in 2000-2016, we performed Rainfall Calculation analysis of 80 rainstorms and short duration heavy rainfalls.

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Analysis Method

Calculation Method for Frequency of Annual Rainfalls. The rainfall data over the years, a total of N, in the order from large to small, got the rank number of each rainfall (i), and then the frequency of annual rainfalls (F) can be obtained by equation (1).

$$F_i = i/(N+1) \times 100\% \tag{1}$$

Linear Trend Method. Linear trend calculation values of meteorological elements with the correlation coefficient r between the time sequence and the natural number sequence B, and the meteorological elements (called trend coefficient) X_i, sample n climate variables, denoted by t_i corresponding to the time, reveal a linear regression of X_i over t_i, that is:

$$X_i = a + b\ x\ t_i \tag{2}$$

i = 1, 2, 3, 4…n

Cumulative Anomaly Method. During the study, the cumulative precipitation method (equation 3) was used to analyze the change trend of annual precipitation in Wuhan (Zhang *et al.*, 2008):

$$CA_j = \sum_{i-1}^{j}(xi - \overline{x}) \tag{3}$$

（j ≤ n, n is the Sequence length）

Where CA_j varies from the cumulative first year to j years of an anomaly, the average value for the entire sequence, positive and negative values of CA_j are possible. In this article, we extract only 1-3 extreme points of each sequence, namely extracting only the strongest signal, and continue for 4 years after the extraction.

Calculation Method of the Rainfall Pattern of a Short Duration Rainstorm. Keifer and Chu (1957) given the synthetic storm pattern for

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drainage design. Wang, Zhao and Gong (2015) performed the classification of short-duration rainfall pattern of Beijing with fuzzy identification method and statistical analysis method based on 1-minute interval rain record. Bi, Chen and Yao (2015) analyzed Urban Rainstorm Pattern of Xi'an and calculated the position coefficients of rainfall peaks of 24-h rain. Tang *et al.* (2018) analyzed the spatial and temporal variations of short-duration heavy precipitation through the rain data in Jiangxi during 1961-2015. Here, with the position coefficients of rainfall peaks can calculate the rainfall pattern of short duration rainstorm based on 3-h Rainstorm data. Firstly, the strongest 3-h rainfall must be found out from the rainstorms, and the maximum 1-h and 2-h rainfalls must be found out also from the strongest 3-h rainfall; and then the position coefficients of 1-h and 2-h rainfall peaks will be determined. Finally, the Rainfall Pattern of 3-h Rainstorm will be obtained.

Rainfall Feature Analysis

Annual Rainfall Feature

Frequency Analysis of Annual Rainfalls*.* According to the observation data in Wuhan Rain-gauge from 1951 to 2016, we found that the average rainfall was 1260.9 mm, the maximum rainfall was 2056.9 mm in 1954, the minimum was 726.7mm in 1966. Frequency analysis of annual rainfalls is adopted in Zhejiang Province (Liu *et al.*, 2009), in Beijing Area (Li *et al.*, 2011), in Hunan Province (Kuang *et al.*, 2013), in main river basin in China (Wang, Wang and Zhang, 2018). Based on other studies, if the frequency of rainfalls is less than or equal to 25 percent, the year can be defined as a wet year. If the rainfall frequency is greater than 25 percent and is less than 75 percent, such a year can be defined as a normal water year. If the rainfall frequency is greater than or equal to 75 percent, the rainfall year can be defined as a dry year. From Table 1, it is found that there were 16 wet years with the average rainfall of 1671.5 mm, there were 34 normal water years with the average rainfall of 1217.7 mm, and there were 16 dry years with the average rainfall of 942.1 mm (Table 1 and Figure 1).

Table 1. The Calculation results of Annual Rainfall frequency in Wuhan from 1952 to 2016.

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No	Year	R (mm)	F (%)	No	Year	R (mm)	F (%)	No	Year	R (mm)	F (%)
1	1954	2056.9	1.49	23	2010	1337.9	34.33	45	2013	1079.8	67.16
2	1983	1894.9	2.99	24	1988	1332.3	35.82	46	1972	1075.2	68.66
3	2016	1834.8	4.48	25	1975	1320.2	37.31	47	1961	1061.1	70.15
4	1991	1795.2	5.97	26	1996	1319.5	38.81	48	1952	1052.8	71.64
5	1969	1744.2	7.46	27	1951	1303.3	40.30	49	1986	1050	73.13
6	1998	1729.2	8.96	28	1995	1296.3	41.79	50	2006	1047.1	74.63
7	1989	1654.9	10.45	29	2008	1266.8	43.28	51	1994	1045.5	76.12
8	1962	1645.3	11.94	30	1970	1235.7	44.78	52	1960	1041.9	77.61
9	1982	1632.4	13.43	31	1973	1229.5	46.27	53	1985	1029.7	79.10
10	1980	1623.6	14.93	32	1955	1220.8	47.76	54	2007	1023.2	80.60
11	1993	1584.6	16.42	33	2014	1215.7	49.25	55	1979	1001.9	82.09
12	1959	1575.8	17.91	34	1984	1209	50.75	56	1956	992.9	83.58
13	2004	1572.2	19.40	35	1977	1195	52.24	57	1968	990.6	85.07
14	2002	1516.1	20.90	36	2000	1179.8	53.73	58	2011	987.2	86.57
15	1987	1449.4	22.39	37	1967	1179.2	55.22	59	1974	965.5	88.06
16	1958	1434.5	23.88	38	2009	1158	56.72	60	1997	946.6	89.55
17	2015	1432.8	25.37	39	1981	1154	58.21	61	1965	920.2	91.04
18	2012	1400.1	26.87	40	1953	1132.7	59.70	62	2001	899.8	92.54
19	2003	1386.1	28.36	41	1963	1125.6	61.19	63	1976	890.7	94.03
20	1999	1380.6	29.85	42	2005	1116.6	62.69	64	1978	811.7	95.52
21	1990	1355	31.34	43	1992	1116.4	64.18	65	1971	800.2	97.01
22	1957	1344.8	32.84	44	1964	1091.9	65.67	66	1966	726.7	98.51

Notes: R is the annual rainfall precipitation value; F - Frequency of annual rainfalls.

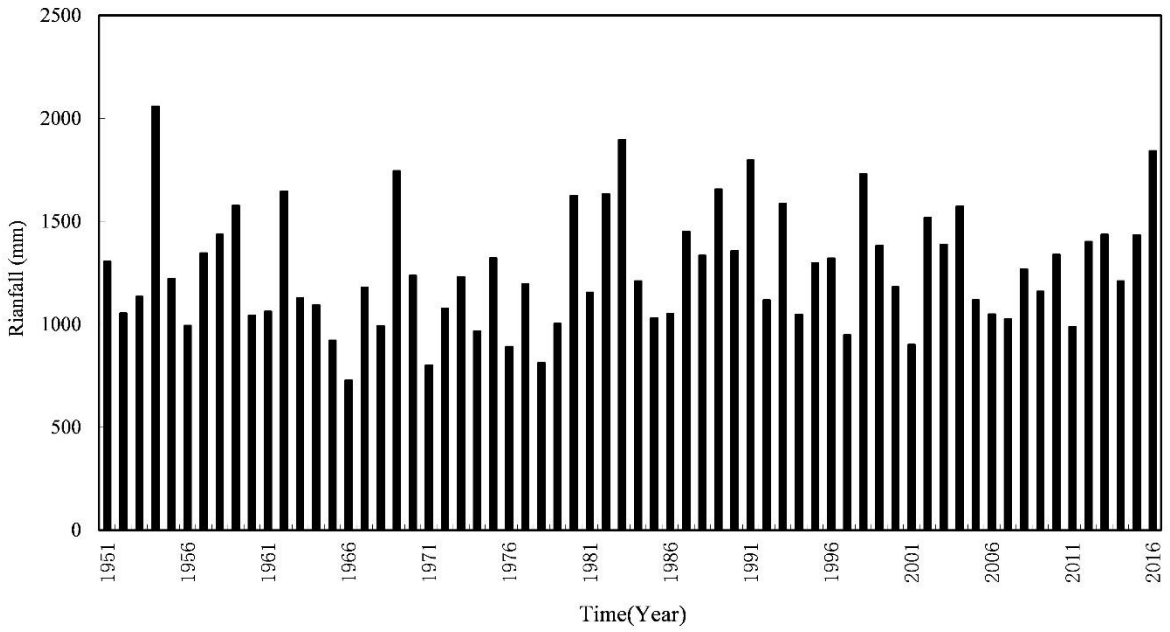

Figure 1. The Annual Rainfall Distribution in Wuhan from 1951 to 2016.

Trend Analysis of Annual Rainfalls. During the studies, the accumulation anomaly method was used to analyze the change trend of annual rainfalls in Wuhan. From Figure 2, one can see that the change trend of annual precipitation in Wuhan in the past 66 years displays two rises and falls overall. Namely, the annual rainfall possessed the rising trend from 1951 to 1960's beginning, when reached the maximum value. Then the annual rainfall precipitation began to reduce gradually to the lowest value from 1960's to 1970's. At the beginning of 1980's, the annual rainfall began to rise from 1980's to 2004. Then the annual rainfall began to fell again until 2011 and rose from 2012. It is evident from Figure 2 that an obvious change happened in 1979.

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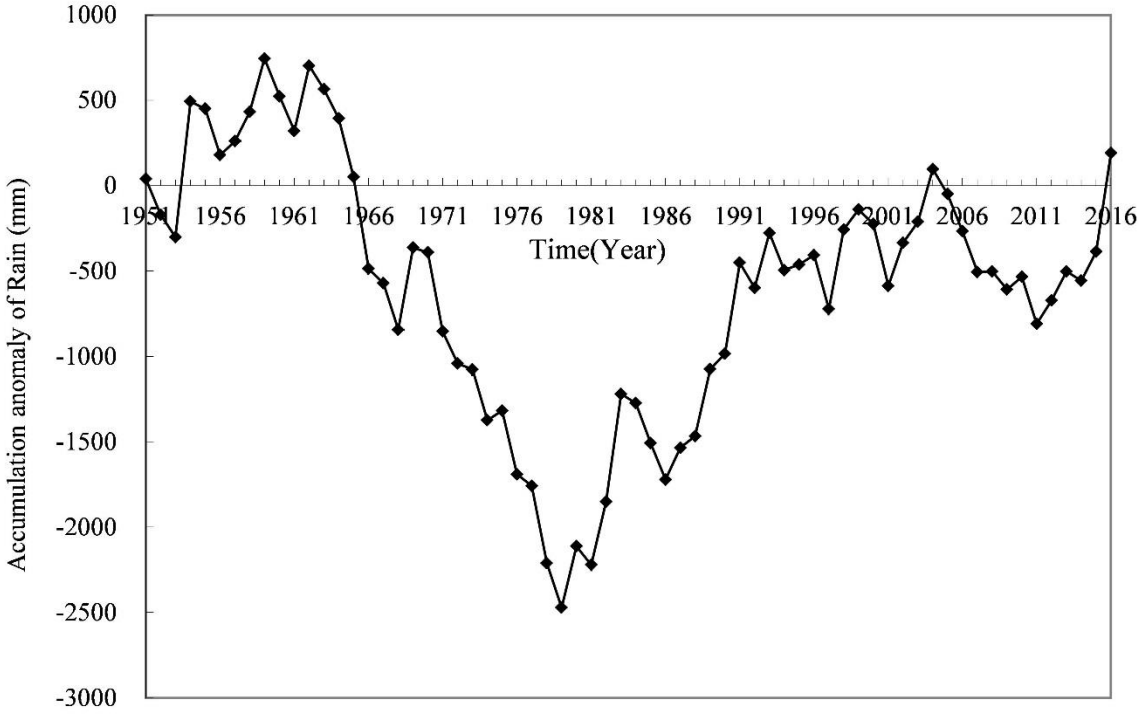

Figure 2. The Accumulation anomaly of Annual Rainfall Distribution in Wuhan from 1951 to 2016.

Monthly Rainfall Feature

Based on the statistics and analysis of rainfall data from 1951 to 2016 in Wuhan rain-gauge, the average, maximum and minimum rainfall precipitation of every month from 1951 to 2016 are given in Table 2. It was found that the rainfalls concentrated mainly in between April and August, accounting for about 65.8%. The mean monthly maximum rainfall occurred in June (217.9 mm), followed by July (189.7 mm), May (164.2 mm), April (135.9 mm), and August (118.9mm); the maximum monthly rainfall of 758.4 mm happened in July 1998 (See Table 2 and Figure 3).

Table 2. The statistics results of the Monthly Rainfall Feature in Wuhan from 1952 to 2016.

	Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec

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Rainfall (mm)	Ave	39.8	61.3	94.2	135.0	159.3	218.8	200.1	119.6	77.2	74.3	56.2	29.2
	Max	107.7	183.1	225	333.6	354.9	522.8	758.4	482.5	219.4	409.2	166.8	107.3
	Year	2000	1990	1992	2002	1954	1959	1998	1969	1973	1983	1967	1968
	Min	0	1.8	16.6	22.9	36.2	13.1	28.9	0.3	1	0	0.2	0
	Year	1963	1968	1962	2000	1981	1963	1978	1966	2001	1979	1995	1999

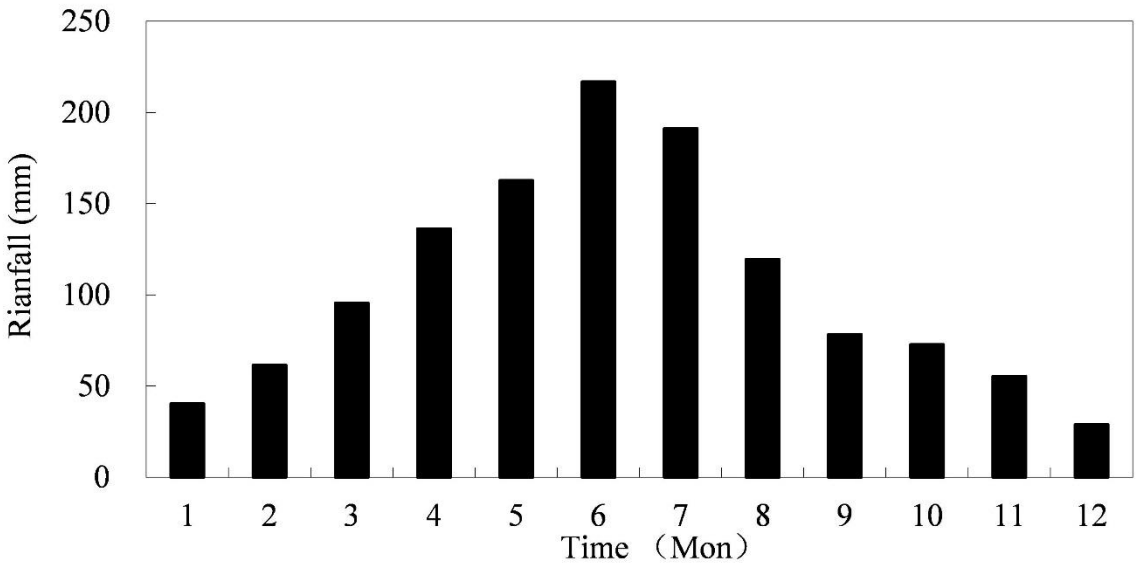

Figure 3. The Distribution Feature of Average Monthly Rainfall in Wuhan from 1951 to 2016.

Distribution and Trend analysis of Rainstorms

Based on the rainfall data in Wuhan from 1951 to 2016, the days of a rainstorm and heavy rainstorm are calculated and the results are shown in Figure 4 and Tables 3 and 4. It is found that in Wuhan city 309 rainstorm days happened in the past 66 years. The most rainstorm days happened in 1991, there were 12 days, followed by 1954 (11 days), and 2004 (10 days) (Figure 4). Among 309 rainstorm days, rainfalls between 50 mm and 100 mm appeared 244 days, accounted for 78.97%; rainfalls between 100 mm and 200 mm appeared 58 days, accounting for 18.77%; rainfalls between 200 mm and 300 mm happened 6 times, accounted for 1.94%, and the rainfall greater than 300 mm appeared 1 time only (see Table 3).

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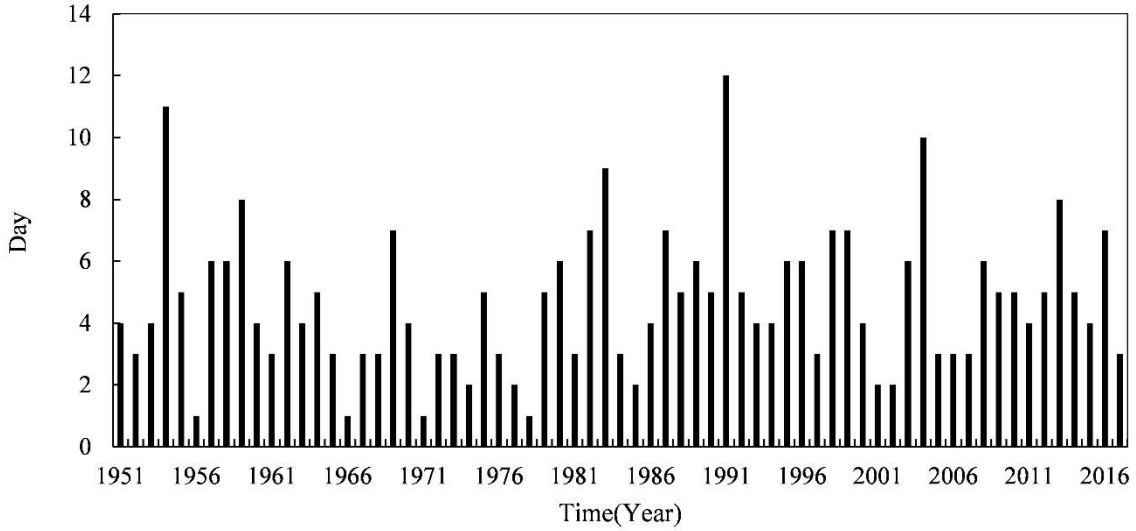

Figure 4. The rainstorm Days in each year from 1951 to 2016.

In Wuhan city, heavy rainstorms happened 65 days in the past 66 years. On average, each year happened 4.69 rainstorm days and 0.98 heavy rainstorm days. Namely, among five rainstorm days, one was a heavy rainstorm. Rainstorms and heavy rainstorms in Wuhan mostly happen in summer, followed by spring, autumn and winter. Among them, rainstorms in summer accounted for 65.05%; heavy rainstorms also concentrated mainly in summer, it accounted for 81.54%. Winter rainstorms in Wuhan only happened 3 days in the past 66 years, less than 1% of the total year (see Table 4).

Table 3. Distribution Feature of different grade rainstorms in Wuhan.

Rainfall range (mm)	50~100	100~200	200~ 300	>300	Total
Number of days	244	58	6	1	309
Percentage (%)	78.97	18.77	1.94	0.32	100

Table 4. Distribution Feature of rainstorm days and large rainstorm days in Wuhan.

Season	Spring	Summer	Autumn	Winter	Total
A	70	201	35	3	309
a	1.06	3.05	0.53	0.045	4.667
Pa(%)	22.73	65.05	11.36	0.97	100
B	9	53	3	0	65

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b	0.14	0.80	0.045	0	0.985
P_b(%)	13.85	81.54	4.61	0	100

A, B are the numbers of rainstorms and heavy rainstorm days; a and b are the average of A and B in 66 years.

Pa and Pb are the percentages of A and B.

Based on maximum daily rainfall data in one year from 1951 to 2016, we found that the trend of maximum daily rainfall was similar to that of annual rainfalls: the maximum daily rainfall firstly descended from 1951 to 1983, then it rose up from 1984 to 2016 (Figure 5).

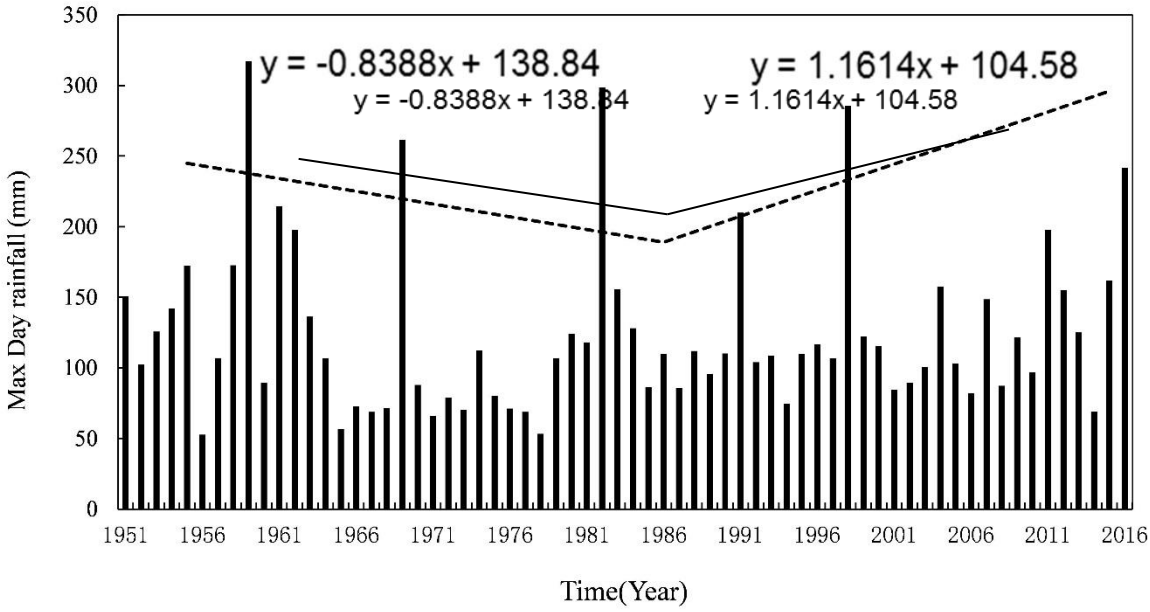

Figure 5. Maximum daily rainfall from 1951 to 2016 (y-axis is maximum daily rainfall; x-axis is the time in years).

Daily Variation of Rainstorms Since 2000

Within this study, we have analyzed 80 rainstorms since 2000, and selected daily rainfalls exceeding 50 mm, to analyze the feature of strong rainfall in a short duration. Among them, 18 daily rainstorms precipitation exceeded 100 mm. The maximum daily rainfall of 245.1 mm happened on July 6, 2016. The statistical results of the rainstorm daily variation since

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2000 are presented in Table 5 and Figure 6. According to Table 5, the average precipitation of 80 rainstorms was 83.28 mm, the maximum 1-h rainfall precipitation of 86.1 mm occurred at 09 am on 19, June 2016. The maximum average 1-h rainfall was 5.74mm at 11:00 am BJT, the maximum average 3-hours rainfall was 15.93 mm in between 10:00 am and 12:00 pm BJT, and the maximum average 6-h rainfall of 29.01 mm occurred between 07:00 am and 12:00 pm BJT.

From Figure 7, we can see two peaks in the rainstorm daily variation feature since 2000, the maximum peak happened at 11:00 am BJT, another one happened at 04:00 am BJT This result differs from the study (Zhang Yin-lin et al,2008), in which the maximum peak was revealed at 05:00 am BJT, and the next one at 10:00 am BJT. The reason for such a deviation may be that the annual rainfall has increased since 2012.

Table 5. The statistical results of rainstorm daily variation from 2000 to 2016 (unit: mm).

Time	Ave1	Max1	Ave3	Ave6	Time	Ave1	Max1	Ave3	Ave6
21:00	3.18	35.60	7.71	17.01	09:00	4.85	33.85	15.90	28.34
22:00	2.76	40.90	7.86	18.17	10:00	5.31	42.10	15.93	27.04
23:00	1.76	19.60	8.31	20.01	11:00	5.74	86.10	14.71	24.60
00:00	3.33	32.00	9.30	22.16	12:00	4.88	49.10	12.44	20.82
01:00	3.22	50.00	10.32	23.18	13:00	4.09	34.70	11.12	17.58
02:00	2.75	29.60	11.70	24.29	14:00	3.47	31.70	9.90	14.44
03:00	4.35	34.58	12.85	25.44	15:00	3.56	33.68	8.38	12.49
04:00	4.60	40.10	12.86	25.95	16:00	2.87	41.40	6.47	
05:00	3.91	30.30	12.59	26.65	17:00	1.96	34.20	4.54	
06:00	4.35	31.65	12.59	28.49	18:00	1.64	36.30	4.11	
07:00	4.33	28.00	13.08	29.01	19:00	0.94	15.59		
08:00	3.91	25.90	14.06	28.77	20:00	1.53	29.15		
Total	83.28	Max of Ave1	5.74	Max of Ave3	15.93	Max of Ave6	29.01	Max of Max1	86.1

Notes: Ave1, Ave3, Ave6 are the average of 1-h rainfalls, 3-h rainfalls, and 6-h rainfalls for 80 rainstorms.

Max1 is the maximum rainfall precipitation averaged for 80 rainstorms.

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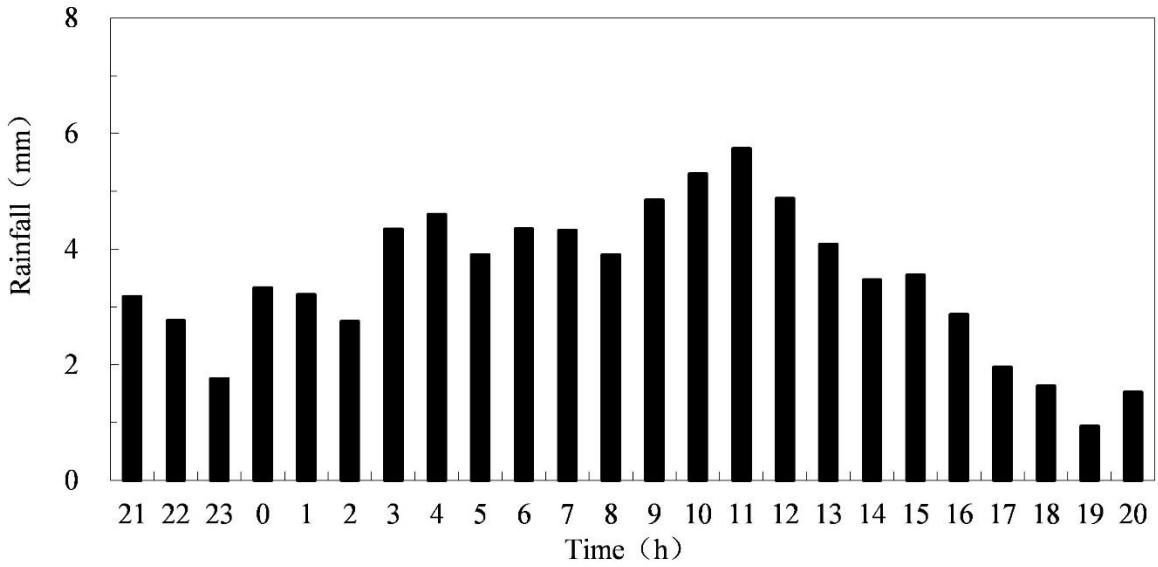

Figure 6. The rainstorm daily variation feature from 2000 to 2016.

Rainfall Pattern of Short Duration Rainstorm

The Rainfall Pattern (RP) of Short Duration Rainstorm is key knowledge for drainage planning in Wuhan city. Based on the drainage and waterlogging planning of downtown in Wuhan city, the rainfall patterns of short duration rainstorms were divided into the following four categories with the different position coefficients of rainfall peaks: RP1: 0< RP <=0.33; RP2: 0.33< RP <=0.5; RP3: 0.5< RP <=0.67; RP4: 0.67< RP <=1.

For this estimation, we selected the strongest 3-h rainfall out of the above-mentioned 80 rainstorms, and then the maximum 1-h and 2-h rainfalls were found within 3-h rainfalls. Thus, the position coefficients of rainfall peaks for 1-h and 2-h rainfalls were obtained as presented in Tables 6-7, and Figures 7- 8.

The position of 1-h rainfalls peaks (RP3-1) coefficients shows that among 80 rainstorms, RP1 appeared 35 times, accounted for 43.75%, RP2 appeared 15 times, accounted for 18.75%, RP3 appeared 14 times, accounted for 17.50%, RP4 appeared 16 times, accounted for 20.00%, and the average for RP3-1 of 80 rainstorms is 0.439 (Table 6, Figure 7).

The coefficients of rainfall peaks for 2-h rainfalls (RP3-2) show that among 80 rainstorms, RP1 appeared 20 times, accounted for 25%, RP2 appeared 29 times, accounted for 36.25%, RP3 appeared 31 times, accounted for

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38.75%, RP4 not appeared, the average for RP3-2 of 80 rainstorms is 0.481 (Table 7, Figure 8).

Table 6. The results for Rainfall Pattern of RP3-1.

Rainfall Pattern	category	RP1	RP2	RP3	RP4	Total
	average	0.439				
Number		35	15	14	16	80
Percentage（%）		43.75	18.75	17.50	20.00	100

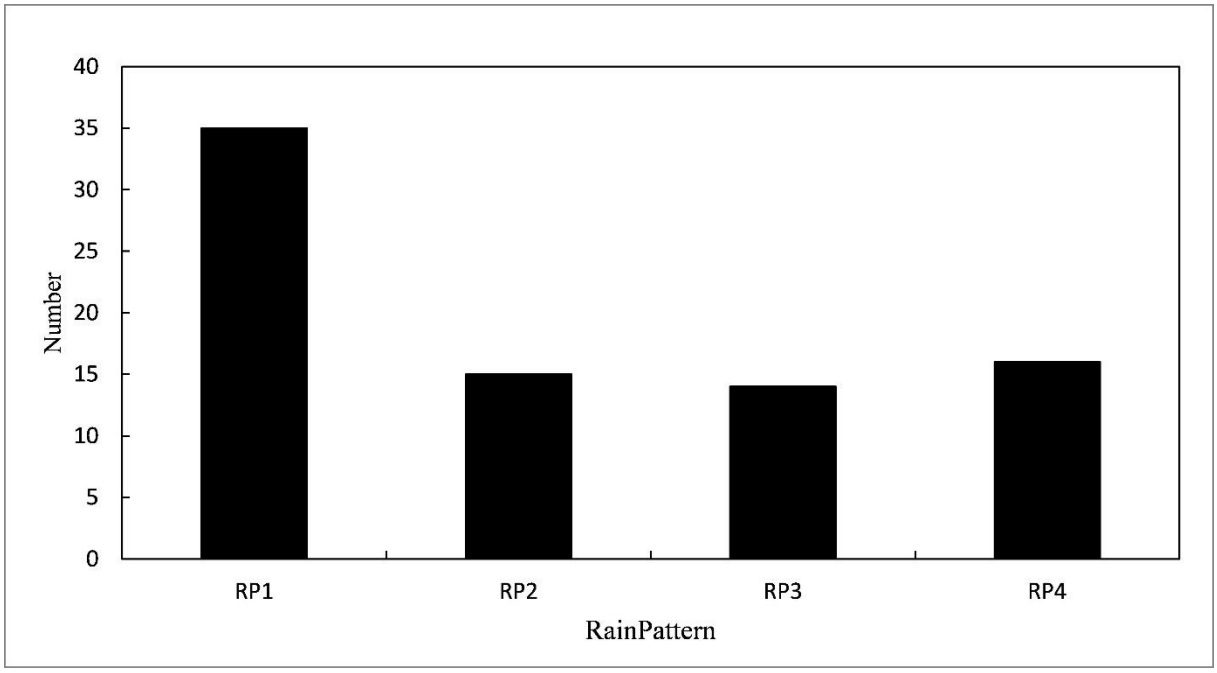

Figure 7. Coefficients of 1-h rainfalls peaks (RP3-1).

Table 7. The results for Rainfall Pattern of RP3-2.

Rainfall Pattern	Category	RP1	RP2	RP3	RP4	Total
	average	0.481				
Number		20	29	31	0	80
Percentage（%）		25	36.25	38.75	0	100

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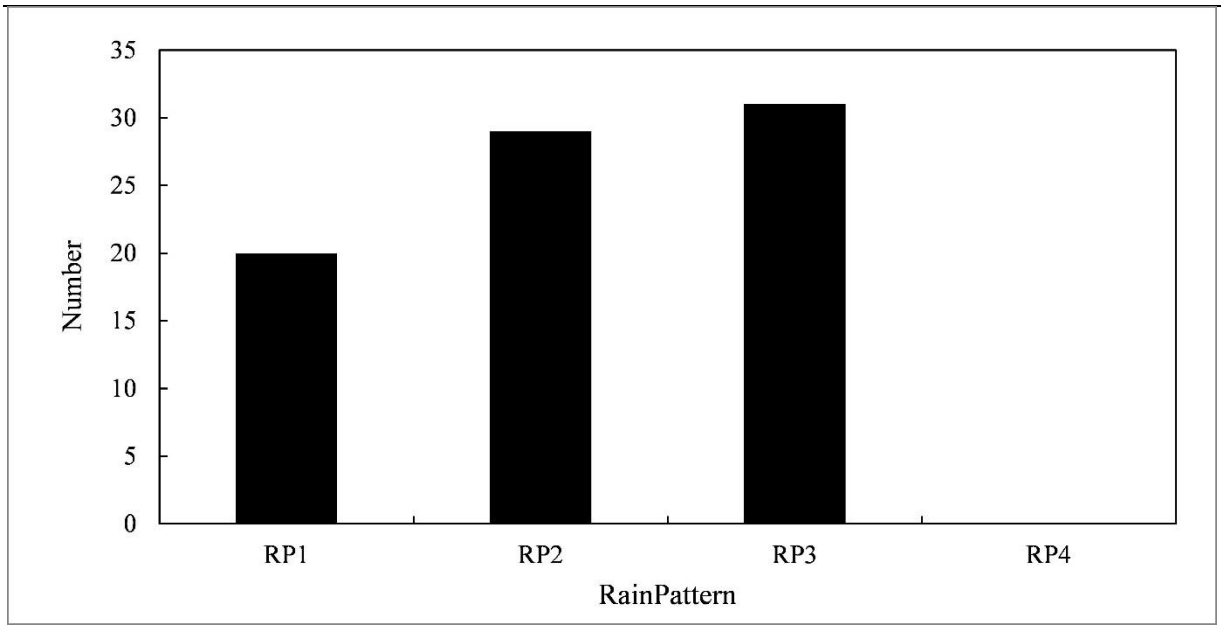

Figure 8. Coefficients of 2-h rainfalls peaks (RP3-2).

Conclusion

Studies of rainfall features and short duration rainfall patterns are of vital importance for many large cities in China to develop their drainage and waterlogging systems. We analyzed data of daily rainfall in 66 years from 1951 to 2016 and performed statistical calculations for precipitation data of 80 heavy rainfalls (daily rainfall >50 mm) from 2000 to 2016 in Wuhan city. Annual and monthly rainfall feature, distribution and trend analysis of rainstorms, daily variation of rainstorms since 2000 as well as short duration rainstorm patterns have been obtained. The conclusions are the following:

1) The average rainfall precipitation was 1260.9 mm from 1951 to 2016; the change trend of annual precipitation in Wuhan in the past 66 years displays two rises and falls. Namely, the annual rainfall had a rising trend from 1951 to at the beginning of 1960's and reached the maximum value. Then the annual rainfall precipitation began to reduce gradually from 1960's to 1970's. At the beginning of 1980's, the annual rainfall precipitation rose again from 1980's to 2004. After that, the annual rainfall decreased until 2011, and finally, it rises since 2012. The critical change in the trend happened in 1979.

2) Rainfalls concentrated mainly in between April and August, accounting for about 65.8%. The mean monthly maximum rainfall occurred in June

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(217.9 mm), followed by July (189.7 mm), May (164.2 mm), April (135.9 mm), and August (118.9 mm).

3）In Wuhan city 309 rainstorm days and 65 large rainstorm days happened in the past 66 years; each year happened 4.69 rainstorm days and 0.98 large rainstorm days. The most number of 12 rainstorm days happened in 1991. The trend of maximum daily rainfall was similar to that of annual rainfalls, the maximum daily rainfalls firstly descended from 1951 to 1983, then increased up to 2016.

4) The daily rainstorm variation since 2000 shows that the average of 80 rainstorms was 83.28 mm, the maximum hour rainfall peak happened at 11:00 am BJT, the maximum average 2-h rainfall occurred between 10:00 am and 12:00 am BJT, and the maximum average 6-h rainfall took place between 07:00 am and 12:00 am BJT.

5) The coefficient of rainfall peaks for 1-hour rainfall, RP3-1, was about 0.439, and the coefficient of rainfall peaks for - hour rainfall, RP3-2, was about 0.481.

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